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THE RÔLE OF THE GLACIAL ANTICYCLONE IN THE AIR CIRCULATION OF THE GLOBE.

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(*Read April 24, 1915.*)

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The Fixed Anticyclones Above Existing Continental Glaciers.

The Anticyclones as Agents of Glacier Alimentation.—In two monographs published in 1910[1] and later in my "Characteristics of Existing Glaciers,"[2] a theory of fixed glacial anticyclones centered over the snow-ice masses of Greenland and Antarctica was put forward upon the basis of a comprehensive review of the results of polar exploration. This theory furnished an explanation for the nourishment of these inland-ice masses through adiabatic melting and vaporization of the ice particles of the cirri, as they are drawn down within the vortex of the anticyclone, and the precipitation of this moisture, generally as fine ice needles, when it comes into contact with the glacier surface and the cooled air layer immediately above it. The obvious application of this theory of alimentation to the even greater continental glaciers of the Pleistocene and earlier glacial cycles, was made in a separate contribution.[3] For these fixed anticyclones themselves, which are deserving of a special name, so much evidence has now accumulated that their existence can hardly be disputed, though differences of opinion will no doubt arise concerning their dominance over or dependence upon the usual migrating cyclonic and anticyclonic movements in the atmosphere.

The Northern and Southern Glacial Anticyclones Compared.—That a great fixed anticyclone exists within the south polar region

[1] "The Ice Masses on and About the Antarctic Continent," *Zeitsch. f. Gletscherk.*, Vol. 5, 1910, pp. 107–120; "Characteristics of the Inland-ice of the Arctic Regions," *Proc. Am. Philos. Soc.*, Vol. 49, 1910, pp. 96–109.

[2] Macmillan & Co., New York and London, 1911, Chaps. IX. and XVI. and afterword.

[3] W. H. Hobbs, "The Pleistocene Glaciation of North America Viewed in the Light of Our Knowledge of Existing Continental Glaciers," *Bull. Am. Geogr. Soc.*, Vol. 43, 1911, pp. 641–659. When this theory of alimentation was announced, I supposed it to be new to science. Professor Hans Crammer has since called my attention to a little-known paper by Fricker published as early as 1893, in which a similar idea was made as a suggestion and at a time when there was little known which could have been cited in its support. (Dr. Karl Fricker, "Die Entstehung und Verbreitung des antarktischen Treibeises." Ein Beitrag zur Geographie der Südpolargebiete. Leipzig, 1893, p. 96; also "Antarktis," Scholl und Grund, Berlin, 1898, pp. 187–188.)

seems to have been early recognized by a number of scientific men, due especially to the writings of the late Sir John Murray, Bernacchi and Buchan. By them it was, however, assumed that this condition was determined in some manner by the earth's southern geographic pole, and was not connected with the inland-ice. A like natural tendency to regard movements within the lower atmosphere as determined primarily by their positions relative to parallels of latitude, is more or less general. As an illustration, it is generally assumed upon the basis of few and scattered observations within all save the central European areas, that the ceiling of the troposphore in its descent from the equatorial regions reaches its minimum altitude above the geographic poles, though it is far more probable that in the northern hemisphere at least its minimum of altitude is to be found to the southward above the continental glacier of Greenland. In the southern hemisphere the Antarctic continental glacier is probably centered near the pole, and in consequence conclusions drawn from geographic positions are there relatively indecisive. During the winter season the great deserts of moderate latitudes become likewise the loci of anticyclones. Their influence upon the general circulation within the earth's atmosphere should be, however, relative to that of the inland-ice small by comparison. It is because the inland-ice masses have a domed surface that they permit the air which is cooled by contact to flow outward centrifugally and so develop at an ever accelerating rate a vortex of exceptional strength. As already pointed out in my earlier papers, this is one of the essential conditions for the formation of strong glacial anticyclones.

Their Strophic Action Believed to be Dependent upon an Automatically Recurring Disturbance of Balance Between Opposing Forces.

The Refrigerating Air Engine.—The strophic action of glacial anticyclones is one of their most marked characteristics, and would appear to be dependent upon the shield-like form of the glacier surface. Opposed to each other are here the abstraction of heat from the air above the glacier surface tending to make it slide off radially, and the increase of temperature due to resulting conden-

sation. Unlike the latter, which is determined by the measure of the vertical component of its fall, the contact cooling is in direct ratio to the time the layer of air rests upon the snow-ice surface. Conditions of calm therefore favor cooling and descent of air currents, as high wind velocity, does the warming and consequent retardation or even reversal of the descending current. It is not surprising, therefore, that the strophic glacial storms are initiated in calm conditions, "work themselves up" or become accelerated to accord with the acceleration of velocity of bodies sliding upon inclined surfaces (here further accelerated by increasing slope toward the margins), and bring about their own extinction when the air passes over the surface too rapidly for surface cooling to exceed or equal adiabatic warming. The sudden check in the outward flow of air, which is one of the most striking features of these strophic movements, in turn promotes new surface cooling and causes the precipitation of fresh snow within the zone of near contact to ice, thus often taking place with the sun but little obscured. In the automatic recurrence of similar movements the glacial anticyclone thus bears considerable resemblance to the hydraulic ram.

The Lines of Evidence for Fixed Glacial Anticyclones.

The Earlier Evidence.—The observational evidence which in earlier papers was adduced in support of the existence of the glacial anticyclone above continental glaciers, was drawn chiefly from the then available reports upon exploration of the inland-ice masses of Greenland, Antarctica, and Northeast Land (Spitzbergen). This evidence may be profitably summarized under the following heads:

1°. Centrifugal flow of surface air currents above inland-ice masses.

2°. Outward (centrifugal) sweeping of surface snow largely derived from the central areas, and its deposition and accumulation as a marginal fringe about the inland-ice.

3°. Snow in large part wind-driven above the sloping portions of the ice mass.

4°. Sudden warming of the air at the end of the blizzard—foehn effect in descending currents.

5°. Behavior of upper air currents and movements of the cirri.

6°. The evolution of the Antarctic blizzard and its termination.

7°. Areas of relative calm corresponding to the flat central bosses of the ice domes.

8°. Air highly charged with moisture within the flat central area of calms, and precipitation of snow or ice near the glacier surface.

Confirmation in Later Exploration.—In the three years which have elapsed since the appearance of my "Characteristics of Existing Glaciers," important new explorations have been carried out; the inland-ice of Antarctica has been twice penetrated to the southern geographic pole and new areas have been explored; several crossings of Greenland have been made along new routes; and full reports upon some earlier explorations have become available. It is proposed, therefore, to review the evidence and show how this has been enlarged by the recent observations; as well as to add evidence along hitherto undeveloped directions. Such a discussion of the evidence seems to be called for at the present time, since in a paper recently read before the Royal Meteorological Society, Brooks has presented this theory as his own, merely citing my book for references to glacial conditions.[4]

Evidence for More than One Anticyclonic Center Above Each of the Greater Areas of Inland-Ice.

Greenland.—The three transections of the Greenland continent which have now been made within the central and southern portions, have revealed the fact that there are at least two higher plains upon the snow-ice surface which are separated by a depression. This depression clearly lies to the northward of de Quervain's route, since his summit level is considerably lower than that of either Nansen or Koch and Wegener, though like Nansen's, his highest point is found near the east coast. The southern of the two nourishing centers of the Greenland ice-sheet is thus located toward the east coast and south of the Arctic circle, whereas the other center lies toward the west coast from the medial line of the continent,

[4] Charles B. Brooks, "The Meteorological Conditions of an Ice Sheet and their Bearing on the Desiccation of the Globe," *Quart. Jour. Roy. Meteorol. Soc.*, Vol. 40, 1914, pp. 53–70.

and in an as yet undetermined latitude, though certainly well to the northward of Disco Island (Fig. 1).

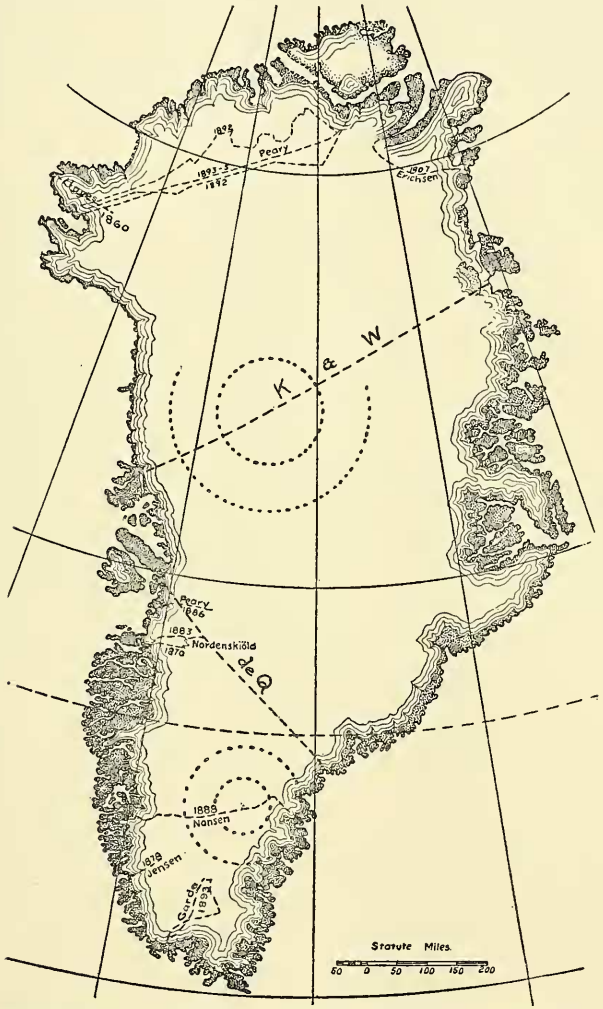

FIG. 1. Sketch map of Greenland to show roughly the position of the ice domes within the central and southern portions.

Antarctica.—This discovery that Greenland is provided with more than one nourishing center for its inland-ice, is wholly in accord with what has now been learned concerning the Pleistocene continental

glaciers of North America, which had the Keewatin, Labradorean and Patrician nourishing centers that repeatedly waxed and waned so as to reach their several maxima at different times (Fig. 2).

FIG. 2. Map showing the known anticyclonic centers of the Pleistocene continental glacier of North America.

From the Antarctic region the experiences of Mawson strongly indicate a near-by anticyclonic area probably located near the mag-

netic pole.[5] Within a vortex of this nature the wind velocity is determined by angular velocity multiplied into the radius, and hence one of relatively small dimensions should exceed in vigor one that is spread over a vast field and in which the steeper marginal area bears a smaller ratio to the whole. Mawson has expressed the belief that his base was near the center of a permanent anticyclone.[6]

The Centrifugal Flow of Surface Air Currents Above the Inland-Ice Masses.

Early Evidence from Greenland.—In 1911 when my work on glaciers was published, evidence was available upon this from both the eastern and western coasts of southern Greenland in latitude 64° (Nansen), from west Greenland in latitude 69° (Peary and later de Quervain and Stolberg[7]), from northwest Greenland in latitude 78–83° (Peary), and from northeast Greenland in latitude 77° to 82° (Trolle). With the exception of the first and last mentioned, these data applied exclusively to the western coast where the prevailing surface winds come from the easterly quadrants.

Later Confirmation.—The later evidence for the centrifugal flow of surface air is ample and throughout confirmatory. De Quervain, who crossed the inland-ice in 1912 between the latitudes of 66° and 68°, found head winds while ascending the west slope, but winds from behind during his descent to the east coast.[8] Referring to the low temperatures and the wide diurnal temperature range within the central area, de Quervain says:

> "It is the cold air of this middle part which even in summer streams like water from off the high surface toward all margins, deviated to the right in consequence of earth rotation" (p. 137).

Measurements of snow temperature made at different depths show

[5] Sir Douglas Mawson, "Australasian Antarctic Expedition 1911–1914," *Geogr. Jour.*, Vol. 44, 1914, pp. 257–286.

[6] L. c., p. 69.

[7] The first Swiss expedition, which penetrated some seventy miles from the coast (A. de Quervain und A. Stolberg, "Durch Grönlands Eiswüste," Strassburg, 1909).

[8] A. de Quervain, "Quer durchs Grönlandeis, Schweizerische Grönland-Expedition 1912–13." Reinhardt, München, 1914, 196 pp., 15 pls., 37 figs. and map. Also personal communications.

how exactly the air temperature follows that of the snow (p. 94). The diary of the journey (pp. 85–104) shows that for the first three weeks on the inland-ice the wind blew almost uninterruptedly down slope from in front, became more variable and shifting on the plain with slope a few seconds of arc, and reversed direction and blew from the northwest soon after passing the divide, where slopes became 8′ of arc to the eastward.

Koch and Wegener in their transection of the Greenland continent at its widest section (between latitudes 72° and 73°) encountered essentially the same conditions, the outward blowing currents constituting a veritable succession of storms whose vigor increased toward both margins of the section.[9]

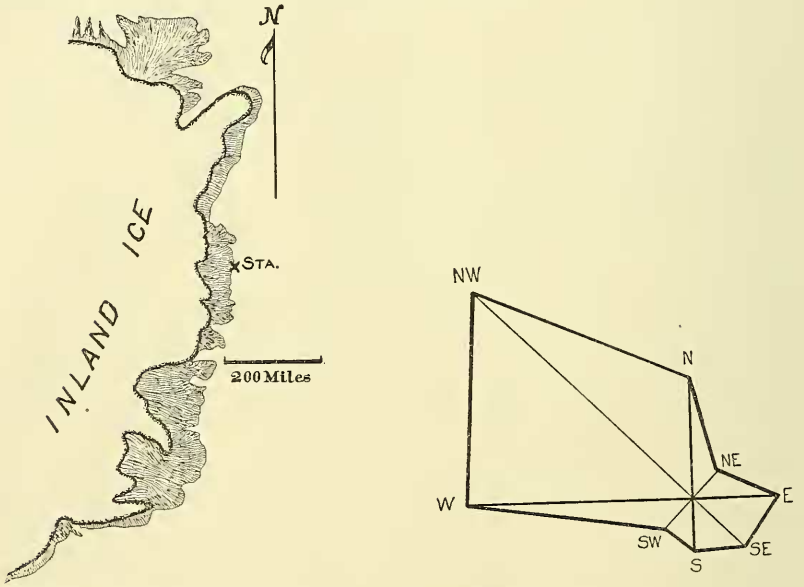

Fig. 3. Frequency wind-rose at Danmarks-Haven in northeast Greenland and (at the left) a sketch map showing location of the station with reference to inland-ice (after Wegener).

From northeast Greenland there was available at the time of my earlier discussions of the glacial anticyclones, only a preliminary

[9] J. P. Koch, "Unsere Durchquerung Grönlands 1912–1913," *Zeitsch. d. Gesellsch. f. Erdk. z. Berlin*, 1914; Alfred Wegener, "Vorläufiger Bericht über die wissenschaftlichen Ergebnisse der Expedition," ibid.

statement concerning the prevailing direction of surface winds at the Danish base near Cape Bismarck. More recently (1911) the full meteorological report by Wegener has been issued; and, confirming the earlier statement, shows that all strong winds come from the westerly (inland-ice) quadrants. The frequency wind-rose to cover the entire period of two years over which the observations extended, is reproduced in Fig. 3.[10] If the wind force had been taken account of, the easterly sections of the rose would have almost disappeared, since easterly winds are always light sea breezes, which at an elevation of only 1,000 meters have been completely overwhelmed by the northwest winds.[11] In this rose the dextro-rotatory deviation of the down-slope winds is apparent.

Early Evidence from Antarctica.—Over the Antarctic inland-ice the law of surface air circulation had been clearly indicated by the results of exploration at the time of my early discussion of the subject. The more important data had been derived from the sledge journeys of Captain Scott, Sir Ernest Shackleton, Professor David and Dr. von Drygalski. As early as 1902 Captain Scott had ascended the Ferrar glacier outlet to the inland-ice above the mountain rampart and pushed west southwestward over it for a distance of two hundred miles, ascending on ever decreasing grades to the farthest point attained, and encountering winds of nearly constant direction coming from the south-southwest. The prevalence of such winds was demonstrated by a single set of sastrugi which pointed in the same direction (see Fig. 4).[12] Shackleton on his polar journey ascended the Beardmore outlet and for a like distance of two hundred miles over the inland-ice found strong winds blowing from the southerly quarter and sastrugi pointed in the same direction. David pushed northwestward from Ross Sea over the inland-ice to the south magnetic pole, crossing over a crest in the ice and descending on low grades during the last stage before reaching the pole. Here the same rule of distribution of currents applies,

[10] A. Wegener, "Med. om Grönland," Vol. 42, 1911, pp. 324–326.

[11] Wegener, "Med. om Grönland," Vol. 42, 1909, pp. 73–75.

[12] For this and other references to work published before 1910, see "Characteristics of Existing Glaciers," Chapters XIV.–XVI.

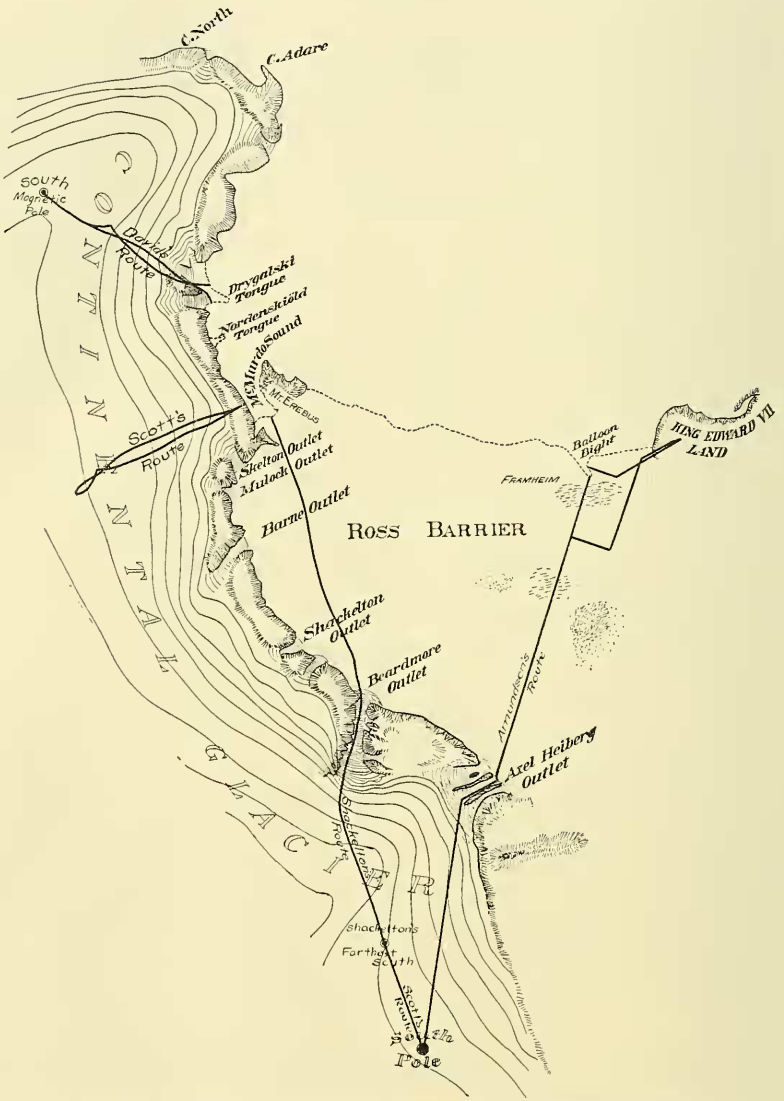

Fig. 4. Map of South Victoria land showing the sledge routes of Scott, Shackleton and David over the inland-ice.

for during the ascent he encountered northwest winds with sastrugi pointing toward the same quarter, but after passing the divide and on the down grade winds blew from behind—southeast. These observations were fully confirmed by the return journey

In Kaiser Wilhelm land also the report of von Drygalski shows that the prevailing winds blow downward off the inland-ice onto the sea and the shelf-ice in front, being deviated to the left—the prevailing strong winds are from the easterly quarter.

Later Confirmation.—Later data which bear upon the problem are derived from the Amundsen and the second Scott south polar expeditions, from the second German expedition to the Antarctic commanded by Filchner, and from the Australasian Antarctic expedition of 1911–14 under command of Dr., now Sir Douglas, Mawson. The route of Captain Amundsen passes through the mountain rampart which hems in the inland-ice, keeping a direction diagonal to it and for some distance after leaving the outlet behind taking a course near a high mountain range. The few data upon wind directions which he has jotted down in his narrative, appear to indicate local currents controlled by these mountains until he had reached the 88th parallel, where he entered an area of calms and light variable winds.[13] The second Scott expedition inasmuch as it followed the route of the earlier Shackleton expedition, has for the greater part of the distance, or until it entered the area of calms, served only to confirm the prevalence of outwardly flowing wind currents described by Shackleton.[14]

The recent Australasian expedition supplies evidence from a new quarter—the long coastal area near the Antarctic circle and to the westward of the Ross Sea, on which coast the inland-ice is not held in restraint by any barrier of mountains, as is the case in South Victoria Land. Along this coast, summer and winter alike, almost incessant storms blow off the ice onto the sea. These outwardly directed storm winds tend to keep the near sea area clear of pack-ice but offer great difficulties in the way of effecting a landing at all save those rare occasions when the force of the wind falls away.[15]

In Prince Regent Luitpold Land, where the later German expedition effected a landing upon the inland-ice—here likewise unconfined by a mountain wall and with partially detached shelf-ice in

[13] Roald Amundsen, "The South Pole," Vol. 2, 1913.

[14] "Scott's Last Expedition," Vol. 1, Chapters XVII–XIX.

[15] Sir Douglas Mawson, "Australasian Antarctic Expedition 1911–14," *Geogr. Jour.*, Vol. 44, 1914, pp. 257–286, maps and plates.

front—much the same conditions obtain, the wind blowing out to sea with velocities sometimes as high as 40 m.p.s.[16]

Outward Sweeping of the Surface Snow which Falls Over the Central Areas of the Ice Domes, and its Accumulation About Their Margins.

The Centrifugal Snow Broom.—What may be characterized as the centrifugal snow broom which sweeps out snow deposits from the central areas and collects them upon and about the margins of continental glaciers, is a necessary consequence of strong anticyclonic conditions; and its work is in evidence within all areas where inland-ice has been extensively explored.

From observations by Wegener, a wind velocity of 6–7 m.p.s. raises the snow lying upon the ground and sets it in motion along the surface at heights up to several decimeters (a foot or thereabouts). With wind velocities of 10–15 m.p.s (22.4–33.6 miles per hour) the migrating drift snow rises in a layer several meters in height and interferes seriously with seeing conditions. With velocities of 20 m.p.s. (44.7 miles per hour), the snow is carried to a height of 20 meters, or over sixty feet, and much higher in the lee of obstructions in its path.[17]

The Sweepings Below Outlets.—It is obvious that the results of snow drifting by centrifugal surface currents above inland-ice will be different according as the ice mass has been built up within a rampart of mountains (South Victoria Land and the greater part of Greenland), or as it has been allowed to shape itself independent of such retaining walls. In the former case the drift snow pours out along the courses of the outlet glaciers to form characteristic aprons at their bases,[18] or perhaps to produce definite fringing gla-

[16] "Deutsche Antarktische Expedition, Bericht über die Tätigkeit nach Verlassen von Südgeorgien," *Zeitsch. d. Gesellsch. f. Erdkunde z. Berlin,* 1913, p. 15; see also, *Kön. preusz. Meteorol. Institute,* Abh., Bd. 4, Heft II., p. 9.

[17] *Med. om Grönland,* Vol. 42, p. 345.

[18] In the light of observations by Scott, Shackleton and David in South Victoria Land, it seems probable that these apron-like snow deposits in the form of dry deltas are due largely if not wholly to this cause. Not only have explorers observed the rapid collection of the drift snow at the base of the Beardmore outlet, but this origin is probable for the reason that accord-

ciers such as have been described by Chamberlin[19] and Salisbury[20] from northwest Greenland, and by the Danes in northeast Greenland.[21]

Shackleton, who advanced over the inland-ice in his southern journey on a layer of granular surface snow, returned over a marble-like floor from which the snow had all been swept by the fierce blizzard encountered near his farthest south. On arriving at the Beardmore outlet, he found the lower forty miles of the stream buried deep under great drift accumulations. Scott on his last expedition was much less fortunate while on the plateau, and the burden of his diary is a prayer for strong wind to clear the surface. As is well known, he encountered heavy sweepings of powdery drift snow at the base of the Beardmore, both during his advance and on the return, and his floundering progress through this soft snow was a main contributing cause of the final disaster which overtook the expedition.

From what is known of the characters of freshly precipitated snow at different air temperatures, it is possible to rather definitely ascribe the enormous snow drifts which piled up for four consecutive days upon the Beardmore glacier apron as the *chasse neige* in process of melting as a result of adiabatic rise in temperature in descending currents. This snow, Captain Scott tells us, was the fine powdery type, though the temperature was phenomenally high ($+27°-31°$ F.), stuck to hair and beard, and produced pools of water everywhere.[22] On the return the snow here was soft, loose and sandy, and sledge work was like "pulling over desert sand."[23]

Marginal Accretions of Snow.—Valuable new observations which bear strongly upon this point, have been supplied in the preliminary report upon the crossing of Greenland by Koch and

ance of *surface* level is generally observed to characterize the junctions of tributary with main glacier streams wherever snow drifting plays only a secondary rôle.

[19] *Jour. Geol.*, Vol. 3, 1895, p. 579.

[20] L. c., p. 886.

[21] Koch und Wegener, "Die glaciologischen Beobachtungen der Danmark-expedition," *Med. om Grönland,* Vol. 46, 1912, Chaps. VI.–VII., pls. and figs.

[22] "Scott's Last Expedition," Vol. 1, pp. 335–339.

[23] L. c., p. 396.

Wegener. They report almost continual storms in all save the highest section of their journey, the wind descending the slopes and filling the air with drift snow. Within the marginal portions of their section, it was established that the finely granular surface layer of snow is joined abruptly to a more coarsely crystalline subjacent layer and corresponds to the annual deposit. This layer was by a series of measurements shown to vary in thickness from 20 cm., or about eight inches, in the central portion, to one half meter (or about two and a half times that thickness) near the east coast, and a meter (or five times this thickness) near the west coast. Schematically represented with grossly exaggerated scales, this distribution is expressed in Fig. 5. It was further determined that the snow

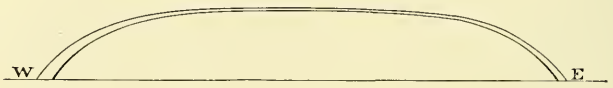

Fig. 5. Diagram to illustrate the marginal thickening of annual snow deposit upon the Greenland continental glacier due to drifting on radial lines.

deposit at Borg, the winter station upon the inland-ice though relatively near its margin, was less than on the coast to the eastward.[24]

Still more recently has appeared the preliminary report of Mawson upon the Australasian Antarctic expedition, in which he tells us that at the winter station on the margin of the inland-ice, the winds which blew down slope and off shore raised "a sea of drifting snow which poured fluid-thick over the landscape."

"For months the drifting snow never ceased, and intervals of many days together passed when it was impossible to see one's hand held at arm's length. The drift snow became charged with electricity and in the darkness of the winter night all pointed objects and often one's clothes, nose, and finger tips glowed with the pale blue light of St. Elmo's fire. . . . Such weather lasted almost nine months of the year. Even in the height of summer, blizzard followed blizzard in rapid succession."[25]

Where tongues of ice extended out to sea from the shore, snow collected upon them though the marginal slopes were swept free of it by the force of the blizzard.[26]

[24] A. Wegener, "Vorläufiger Bericht über die wissenschaftlichen Ergebnisse der Expedition," *Zeitsch. d. Gesell. f. Erdkunde z. Berlin*, 1914.

[25] Sir Douglas Mawson, "Australasian Antarctic Expedition, 1911–14," *Geogr. Jour.*, Vol. 44, 1914, pp. 269.

[26] Mawson, "The Home of the Blizzard," 1915, Vol. 2, p. 33.

Sudden Warming of the Air at the End of the Glacial Blizzard—Foehn Effect in Descending Currents.

Intensive Foehn Effective in Outlets.—This familiar foehn effect is so general a phenomenon about the margins of both the great continental glaciers that it has long been recognized.[27] The general rule holds that the temperature of the air rises as the blizzard is evolved.[28] Wherever a mountain rampart exists, the elevation of temperature becomes accentuated within the glacier outlets, and melting in Antarctica is almost unknown except under these conditions. An interesting example of this which has not before been emphasized, is supplied by Armitage, who on the first ascent of the Farrar outlet found a stream of water seven feet in width and nine inches deep flowing beside the ice.[29] The effect of similar currents of water was noted by David on his ascent to the plateau from McMurdo Sound. A remarkable instance, also, with long continuance of high temperature, is that above cited from Captain Scott's journal, while camped on the apron below the Beardmore outlet.

The Greenland Foehn.—The characteristic Greenland foehn has been subjected to a special study by Stade, the meteorologist of the Berlin Geographical Society's expedition to Greenland.[30] He finds that the temperature changes are much more pronounced during the winter season, the rise on March 5, 1893, having been 12° C. and probably much more within the space of a few minutes. Stade's conclusion is that these foehn winds are connected with low areas moving northward in the Davis Straits, the maximum of air temperature and the minimum of relative humidity corresponding either exactly or approximately with the minimum of pressure at the station. De Quervain's later studies would indicate that Stade's moving depressions may better be regarded as pulsations within a stationary low pressure area lying over Davis Straits and Baffin's

[27] See "Characteristics of Existing Glaciers," pp. 149–150, 268–271.

[28] Cf. Mawson, "The Home of the Blizzard."

[29] A. A. Armitage, "Two Years in the Antarctic," London, 1905, p.

[30] Dr. H. Stade, "Über Foehnerscheinungen an der Westküste Nordgrönlands und die Veränderung der Lufttemperatur und Feuchtigkeit mit der Höhe. Nach den Beobachtungen auf der Station Karajak, Grönland Expedition 1891–93," Vol. 2, 1897, pp. 501–533.

Bay. It would then seem more in harmony with the facts to reverse this conception and assume that the low pressure area is stimulated to greater vigor by the arrival of the strong winds of the glacial blizzard over the inland-ice.

Foehn Level and Foehn Clouds on Greenland Coast.—In northeast Greenland the monumental investigations by Wegener furnish us with clearly defined results. In addition to full station weather observations collected for a period of two years at two neighboring stations—Pustervig, relatively near the inland-ice margin but within a canyon, and Danmarks-Haven, fifty miles further outward and upon the coast;[31] we have systematic observations with kites and captive balloons in ascents to heights generally of 1,500 meters and occasionally of 3,000 meters.[32] The results indicate that the larger weather disturbances are in the main controlled by the great high pressure area lying over the continent, that two strongly marked lower inversions in the atmosphere occur almost uniformly; the first within the lower 200 meters and explainable by surface radiation and latent heat of freezing and thawing, while the second lies between a thousand and fifteen hundred meters of altitude, at which level the great outward streaming from the inland-ice pours over the rock plateau to the westward of the station (average height of the plateau 800 meters). The most prevalent cloud form at the stations consists of a series of flat mushroom shapes in a succession of steps or stages located near the upper inversion level—on an average, 1,200 meters. These being clearly due to foehn conditions, they have by Wegener been given the name, "foehn clouds."

The twenty-three ascents of kites and balloons which were carried out at the time of more pronounced foehn, indicate that owing to the partial disappearance at such times of the lower cold moist layer, the temperature inversion of this lower layer is less pronounced and the temperature fall in the layers above it more pronounced, than at other times—in the most marked instances this fall

[31] A. Wegener, "Meteorologische Terminbeobachtungen am Danmarks-Haven, *Med. om Grönland,* Vol. 42, 1911, pp. 124–355. W. Brand und A. Wegener, "Meteorologische Beobachtungen der Station Pustervig," ibid., 1912, pp. 446–562.

[32] A. Wegener, "Drachen- und Fesselballonaufstiege aus gefuhrt auf der Danmark-Expedition 1906–08," ibid., 1909, pp. 1–75.

is super-adiabatic. The typical foehn cloud layer at 1,200 meters is also at such times much more marked, and up to this level the wind velocity falls off with altitude. Of the greatest significance were the results of ascents made at the time of easterly winds—always light; since these show that the easterly winds fade away below the altitude of 1,000 meters, at which level they become replaced by the westerly winds which are controlled by the anticyclones.[33]

Areas of Relative Calm and of Air Highly Charged with Moisture Corresponding to the Central Plains Upon the Ice Domes.

Few Early Data.—At the time "Existing Glaciers" was published, no observational evidence bearing upon this point was available from either of the large continental glaciers, since neither had been penetrated to the central area. Nansen's crossing of Greenland within its narrowed southern portion, had revealed an area of calm near the divide on his section, but it could not then be predicated that this represented more than the margin of the central ice plain. The most valuable evidence then available was derived from Northeast Land (Spitzbergen), which is covered by a dome of inland-ice about a hundred and eightly miles in diameter and between two thousand three thousand feet in altitude in the central area. This area of inland-ice had in 1873 been penetrated by A. E. Nordenskiöld and Palander, who several times observed the simultaneous fall of irregular ice-grains enveloped in water and of small snow-flakes either rounded or star-like, the ice-grains freezing immediately on falling and becoming attached to the hair or clothes, since the air temperature was $-4°$ to $-5°$.[34]

Recently Acquired Evidence from Antarctica.—During his penetration of the inland-ice area of Antarctica, Captain Amundsen entered near the 88th parallel, what he believed to be a region of permanent calm or of light winds and of generally clear weather. As evidence of this, the snow surface was smooth and with no in-

[33] A. Wegener, "Drachen- und Fesselballonaufstiege," *Med. om Grönl.*, Vol. 42, 1909, pp. 60–75.

[34] Cf. "Existing Glaciers," p. 277.

dication of drifting. To a depth of 2 meters no hard snow layers were encountered, so that the cutting of blocks (for guide cairns) was all but impossible. During the fortnight spent within this region the sky was clear with light winds, except on two days when there were snow flurries at intervals. The brightening after the snow was accompanied by such a high sun heat that even with most clothing removed the perspiration poured from the bodies of the men.[35]

Captain Scott, who entered the same general region about a month later, found conditions of atmosphere and snow which during the three weeks of his stay within it, agreed strikingly with those described by Amundsen. After passing the latitude 87½°, hardly a day passed that he did not jot down in his diary the fact of variable light winds and the noteworthy softness of the snow surface, several times expressing his opinion that the area is one of light winds. He was evidently puzzled by the appearance of the clouds, "which don't seem to come from anywhere, form and disperse without reason." Again he describes them as "coming and going overhead all day, drifting from the S. E., but constantly altering shape. Snow crystals falling all the time" (Vol. 1, p. 370). On January 19 on the return from the pole, he notes, "Snow clouds, looking very dense and spoiling the light, pass overhead from S., dropping very minute crystals; between showers the sun shows and the wind goes to the S. W."

Again and again he calls attention to the dampness and the chill in the air, so that when the temperature is observed, all are surprised that it is not lower. The sun was often shining through the snow mist, and bright sunlight and overcast sky interchanged with kaleidoscopic suddenness. Near the margins of this area snow blizzards were experienced, but in comparison with the Barrier blizzards Scott notes that the wind was surprisingly light. Temperatures rise after the blows. Within this central area the sastrugi are found in isolated areas, show cross directions and general lack of constancy. The snow got softer the farther they went to the southward, and it was soft below the surface also "as deep as you like to dig down." Yet with all the wind variations, there was evidently a preponderance of southerly and southeasterly winds. Like

[35] Roald Amundsen, "The South Pole," Vol. 2, Chapters XI.–XIII.

Amundsen, Scott noticed a slight descent toward the pole from latitude 89½°, which, taken in connection with Shackleton's observations, would indicate that a crest of the inland-ice lies to the westward of the routes.[36]

Recent Data from Greenland.—The account of de Quervain's transection of Greenland in 1912 in latitudes 66° to 70° N., affords strikingly similar pictures. Whereas for the first three weeks of the journey upon the inland-ice, or until the ascent had been made to the interior plain, the outward blowing winds had been so constant as to be depended upon in laying the course; shifting winds of light force were encountered upon the plateau, and when the grade had been reduced to 3″ of arc even west or northwest winds blew for short intervals. The air appeared to be strongly saturated with moisture, and at times only the heads of the party would be visible at moderate distances because of the bank of mist, and beards, chins, caps, etc., became frozen into solid masses of ice. Once over the divide, where the slope took on a descent of 8′ of arc, the wind blew strongly from the northwest.[37]

The expedition of Koch and Wegener which crossed Greenland in its widest section (in latitudes 71° to 79°), perhaps furnishes us with the most satisfactory evidence that has yet become available upon meteorological conditions above the central boss of a continental glacier; for the reason that no other expedition has penetrated so close to the heart of the area. From the preliminary report we learn that above the flat dome of the ice shield, an area of atmospheric calm was encountered and much mist, which in the morning was generally so dense as to hide the sun. The air was so supersaturated with moisture that the clothing was constantly wet and could be dried only occasionally and with much difficulty. Everywhere above the altitude of 2,000 meters the snow surface was granular and underlain by coarser grained material, though without hard separating crusts.[38]

Despite the supersaturation of the air and the frequent deposition of minute ice crystals from the clouds, it is pretty clear that if

[36] "Scott's Last Expedition," Vol. I, pp. 363–383.

[37] A. de Quervain, "Quer durchs Grönlandeis," 1914, pp. 85–137.

[38] Alfred Wegener, "Vorläufiger Bericht über die wissenschaftlichen Ergebnisse der Expedition," *Zeitsch. d. Gesell. f. Erdk. z. Berlin,* 1914.

referred to the plateau surface, the peculiar shifting clouds so often observed by Scott and Amundsen are at a low level. The diurnal temperature chart published by de Quervain for his transection of Greenland, shows that radiation from the surface is apparently but little interfered with by clouds after the central plain has been reached. The abrupt change from this condition to one of small daily range of temperature, is found on both margins of the summit plain.

The Cirri Above and About the Existing Continental Glaciers.

The Earlier Data.—The relative abundance of cirrus and cirro-stratus clouds, not only above but about the margins of the continental glaciers, will be patent to any one who will read the lists of cloud observations which are published in the reports of the exploring expeditions.[39] In 1911 it was possible to cite the observation of Nansen, that during his crossing of the inland-ice though the sky was in the main clear, those clouds which were present were generally the cirri or some combination of these with cumuli or strati. From the Shackleton expedition in the Antarctic it was learned that the upper air currents near the winter station generally appeared to move in from the northwest quadrant and veer southerly as they advanced toward the pole. The "polar bands" or "Noah's Arc" clouds (cirro-strati) in general moved southerly, but to the west of the Ross Sea, the "polar bands" moved in from the north northeast or northeast veering round from the north. Thus, as a general rule, it would appear that in this region the upper currents carrying the cirri move roughly parallel to but in opposite direction from the stronger surface currents. In the same region additional evidence was derived from the behavior of the

[39] See, for example: "Wilkes Exploring Expedition (when off the Antarctic Continent)," Vol. XI., *Meteorology*, pp. 276–291; Mohn und Nansen, "Durchquerung von Grönland," *Pet. Mit.*, Ergänzungsh. 105, pp. 22–29; Duc d'Orleans, "Croisières océanographiques dans la mer du Gronland en 1905, Résultats Scientifiques," Bruxelles, 1907, pp. 52–67; Stade, "Grönland Expedition der Gesellschaft für Erdkunde," Vol. 2, pp. 417–441; Wegener, "Meteorologische Terminbeobachtungen," etc., *Med. om Grönland*, Vol. 42, 1911, pp. 202–311.

vapor cloud above Mt. Erebus, which starts from an elevation of nearly 14,000 feet.

Later Investigations.—In endeavoring to investigate further the movement of the cirri upon the borders of the inland-ice, the data supplied by the Greenland Expedition of the Berlin Geographical Society have been taken into consideration. Stade in his tabulated meteorological data at Station Karajak on the west coast, in some thirty-nine instances has supplied the direction of movement of the cirri observed. These I have plotted to form a wind-rose (Fig. 6),[40] which shows clearly the dominance of movements from the

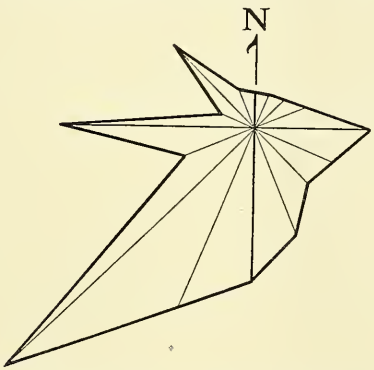

Fig. 6. Wind-rose for the cirri whose direction of motion was observed at station Karajac, West Greenland (several identified doubtfully as cirri are included).

southwest towards the northeast, or in other words in the general direction toward the interior region of the Greenland glacier.[41]

The Evolution of the Glacial Blizzard and its Abrupt Termination in Foehn.

The Sequence of Events.—While there is apparently much in common between the Greenland and the Antarctic glacial blizzards,

[40] H. Stade, l. c., pp. 417–441.

[41] In central Europe Hesselberg has discovered a general correspondence between the drift of the cirri and that of the low pressure areas, but in view of the observations of de Quervain upon the stationary character of the depression over Baffin's Bay, it is unlikely that this conclusion can be applied to the borders of the inland-ice (Th. Hesselberg, "Ueber die Luftbewegung im Zirrusniveau und die Fortpflanzung der barometrischen Minima," *Beitr. z. Physik. d. fr. Atmosphäre,* Vol. 5, 1913, pp. 198–205.

we are indebted especially to Professor David, the meteorologist of the Shackleton expedition, for a careful study of the Antarctic type of blizzard as observed by him at the winter station of the expedition. I shall here cite my earlier summary of the sequence of events with some personal interpretations.[42]

"The sequence of events during a blizzard begins with gentle northerly winds which continue for a day or two during which temperatures are low. David has suggested that during this time air is flowing south to take the place of air whose volume has been reduced as a result of the heat abstracted from it on the ice surface. Then there follow two or three days of absolute calm, during which the temperature continues to fall. Still further cooled upon the ice surface, the air, a week or more after the calm begins, starts to move outward in all directions and so develops (on the edge of the barrier) a southeasterly blizzard. Simultaneously with this movement the steam cap over the volcano of Erebus, which normally indicates an upper current from the northwest, swings round to the north and takes on an accelerated movement, as though it were being drawn from that direction to supply air to the void resulting from the violent surface current toward that direction. Corresponding to the increased velocity, the normal foehn effect near the pole must be much increased as it is also on the descent of the surface current from the plateau. As soon as the warming of the polar air from this cause has become general, the high air pressure of the central area is automatically reduced, and thus the blizzard gradually brings about its own extinction. To the warming effect of the descending air current there is rather suddenly added the latent heat of condensation of the moisture when it is precipitated in the form of fine ice crystals within the air layers just above the snow-ice surface. The rather sudden termination of the blizzard may be thus in part explained. David has suggested that a 'hydraulic ram effect' may be induced in the air of the upper currents, since the steam clouds over Erebus, normally the antitrades, are temporarily reversed in direction at the termination of a blizzard, and for a short interval blow northward."

Source of the Precipitated Snow.—The actual initiation of the strong wind may begin very suddenly, as has been especially emphasized by Simpson[43] and even more strikingly brought out by Mawson.[44] Referring to the source of the moisture of the blizzard as the cirri, I stated in 1911:

"There is, however, the probability that in general this snow or ice is adiabatically melted and vaporized during its descent to the plateau, and subsequently congealed as it mixes with the cold air above the plateau

[42] "Characteristics of Existing Glaciers," pp. 269–270.

[43] "Scott's Last Expedition," Vol. 2, p. 325.

[44] Mawson, "The Home of the Blizzard," Vol. 1, Chap. VII.

surface. This would explain the clear skies which are so general over both Greenland and Antarctica during snows in the higher levels. It is of course true that the latent heat of fusion and vaporization of ice, abstracted as it is from the air during its descent within the eye of the anticyclone, will counteract to some extent the warming adiabatic effect; and it is not improbable that the long duration of Antarctic blizzards and their somewhat sudden terminations accompanied by snowfall are explained in part by the transformations of latent and sensible heat.

"Additional evidence for the continental and glacial rather than the polar nature of the Antarctic anticyclone is derived from the strong blizzards observed at the British winter quarters on McMurdo Sound. *Whereas the lighter gales came from the southeast and indicated a control by local conditions, a blizzard of the first magnitude was not thus influenced, and always swept down from the southwest—that is, from the high plateau, and not from the pole, since otherwise the earth's rotation would have given it an easterly direction.* When its powers begin to wane, it is once more controlled by local conditions and the wind again comes from the southeasterly quarter."

Amundsen's Meteorological Records at Framheim.—Hardly less significant were the directions of prevailing winds observed at Framheim, the winter quarters of the Norwegian Antarctic expedition of 1910–12, when the position of the station is considered in reference to areas of inland-ice and shelf-ice. The great dome of inland-ice of King Edward Land lies to the eastward and southeastward distant only about 115 miles, whereas that of South Victoria Land and its extension to the southeastward, lies a number of times that distance away to the southwestward and westward. Now it was found that easterly winds predominated (31.9 per cent. of the time), with southwesterly and southerly winds next in order (14.3 per cent. and 12.3 per cent. respectively). Southeasterly winds were especially rare, and as calms reigned for a fifth of the time (21.3 per cent.), the winds for four fifths of the period are those accounted for. Earth rotation should deviate original southwesterly winds into a southerly direction, and southeasterly to easterly.[44a]

Alternations of Calm and Gale.—The strophic characteristic of the glacial blizzard thus involves frequent alternation of calms with strong gales, and all systematic observations about the inland-ice reveal this characteristic. As already pointed out, the strophic quality is to be expected from the recurring disturbance of balance and later recovery in opposing forces (ante, p. 188). Below in tabu-

[44a] R. Amundsen, "The South Pole," Vol. 2, pp. 381–382.

lar form are set forth the percentage of calm days to all others as determined at several stations near the margin of inland-ice:

PERCENTAGE OF CALM DAYS TO ALL OTHERS.

	Per Cent.
Danmarks-Haven, Northeast Greenland[45]	26
Cape Adair, South Victoria Land[46]	45
Scott's First Base, South Victoria Land[47]	23
Cape Evans, South Victoria Land[48] (up to 4 miles per hr. 29.8 per cent.)	
Framheim, Whale's Bay[49] (up to 4 miles per hr. 42.2 per cent.)[48]	21.3

THE THEORY OF CIRCUM-POLAR WHIRLS VS. THE GLACIAL ANTICYCLONES.

Views of Ferrel and Hann.—From a theoretical view-point, the theory of circumpolar whirls first enunciated by the American meteorologist Ferrel, has been a most serious obstacle in the way of securing a clear conception concerning the air circulation above continental glaciers. Ferrel's theory assumed that strong westerly winds sweep about the geographic poles with increasing acceleration of velocity and corresponding centrifugal effect, producing polar areas of calm and of low barometer. Of the southern polar region, Hann stated as late as 1897:[50]

> "The whole Antarctic circum-polar area presents us, as already stated, with a vast cyclone, of which the center is at the pole, while the westerly winds circulate round it."

This view was of course largely speculative, and when Bernacchi of the "Southern Cross" expedition had brought out on the basis of observations at Cape Adare the evidence for anticyclonic conditions over the south polar regions, Hann cautiously qualified his earlier statements in the following manner:

[45] Wegener, "Med. om Grönl.," Vol. 42, pp. 325–326.

[46] Bernacchi, in Borchgrevinck, "First on the Antarctic Continent," p. 306.

[47] Shaw, "National Antarctic Expedition, 1901–1904, Meteorol.," Pt. I., 1908.

[48] Simpson, "Scott's Last Expedition," Vol. 2, p. 320.

[49] Amundsen, "The South Pole," Vol. 2, pp. 381–382.

[50] "Handbuch der Klimatologie," 2te aufl., Vol. 3, 1897, p. 543.

"As regards the Antarctic Anticyclone, I have certainly not expressed myself quite clearly in my 'Klimatologie,' as you very fairly point out.

"It is certain that an area of pressure, which is higher than that of the surrounding area, lying over a chilled continent, or over any considerable land area, can coexist with a great polar cyclone, for instance, round the South Pole. The very low temperature can produce in the lower strata of the atmosphere a pressure higher than its environments. The anticyclone, however, must be very shallow, and at a moderate elevation the ordinary circulation of the atmosphere must reëstablish itself. . . . It is just possible that further inland a slight increase of pressure might be observable. There is certainly no chance of the existence of a real continental anticyclone, inasmuch as at Cape Adare the barometer falls from summer to winter."[51]

The above and later qualified statements by Hann[52] fail to take proper recognition of the facts as known at the time, and in treatises on meteorology published within the last five years, the circum-polar whirls are still treated with slight qualifications of statement, and as though in harmony with observed facts.[53]

View of Meinardus.—Probably the fullest discussion of this subject is that of Meinardus in 1909, who is so firmly convinced that the anticyclonic conditions that were encoutered in Kaiser Wilhelm Land at the margin of the inland-ice, cannot have an upward extension beyond 2,000–3,000 meters, that he even prophesied for the interior portions of Antarctica a bare land area destitute of snow.[54] He says:

"The elevated parts of Antarctica above 2,000–3,000 meters extend into the great cyclone of the polar whirl and encounter westerly air currents during the entire year. With this verification, which also further can be supported by certain observations from the marginal region, there follows the conclusion *that the Antarctic anticyclone can in general be present as active element in the air circulation only in the lower parts of the South Polar region.* . . . At the sea level and on the borders of the inland-ice, that

[51] Letter written to Captain R. F. Scott in 1900, *The Antarctic Manual,* 1901, p. 34.

[52] "Lehrbuch der Meteorologie," 2te aufl., 1906, p. 345; Klimatologie, Vol. 1, 1908, p. 334.

[53] Moore, "Descriptive Meteorology," 1910, p. 141. Milham, "Meteorology," 1912, p. 162.

[54] W. Meinardus, "Meteorologische Ergebnisse der Winterstation der 'Gauss,' 1902–03, Deutsche Südpolar Expedition 1901–03," Vol. 3 (*Meteorol.,* I., Vol. 1), p. 332. (The italics are in the original, W. H. H.)

is, within the known coast areas, the anticyclonic conditions do not yet prevail."[55]

Referring to the observations by Captain Scott and by others upon the plateau back of the Admiralty Range in South Victoria Land, Meinardus is quick to seize upon the westerly winds which there prevail as evidence that the anticyclone has at these levels given place to the supposed overlying cyclones; failing utterly to note that the winds are here blowing directly down slope from the ice plateau—that is, radially.[56] Other statements in the report are likewise strikingly at variance with facts either known at the time or revealed by later exploration.

Objective Studies by Barkow in Antarctica.—The first opportunity to measure the upward extension of anticyclonic conditions over Antarctica, has been taken advantage of by Barkow, the meteorologist of the Second German Antarctic Expedition; who at the margin of the inland-ice of Prince Regent Luitpold Land (lat. 77° 45′ S., long. 34° 40′ W.) sent up pilot balloons, one on February 2, 1912, to the extreme elevation of 17,200 meters, or over 8 km. above the base of the stratosphere.[57] These observations disclose the fact that easterly and northeasterly winds prevailed at the time of observation in all levels *up to the ceiling of the troposphere,*[58] whereas with the beginning of the stratosphere, where at an elevation of 9,000 meters the wind turns suddenly through an angle of 180° and blows steadily from the southwest. If, as is probable, the margin of the continent corresponds to the margin of the inland-ice dome, these observations considered with due regard to the known deviation indicate an anticyclone fed by currents above the troposphere. Barkow calls attention to the speculations of Meinardus above referred to, and shows that they are controverted by the results of his observations.

[55] L. c., p. 333. Hardly in harmony with the facts known at the time, since easterly winds, and not westerly, are here the rule (cf. "Existing Glaciers," pp. 264–265, and ante, p. 197).

[56] L. c., p. 334.

[57] E. Barkow, "Vorläufiger Bericht über die meteorologischen Beobachtungen der deutschen antarktischen Expedition, 1911–12," *Ver. d. k. preusz. meteor. Inst.*, No. 265 (Abh., Vol. 4, No. 11), Berlin, 1913, pp. 7–11.

[58] The italics are mine.—W. H. H.

Barkow also carried out kite and balloon ascents, of which a proportionately slight per cent. only failed to show strong inversions of the lower atmosphere, these inversions being proportionately both strong and frequent during the winter season. The entire lower layer of 2,000 meters height was shown to have an average higher temperature than the lowermost layer, the temperature rise from the bottom being often as much as 10° C., and in one instance 19.5° C. In the spring season an alternation of inversions (Blätterstruktur) was observed.

De Quervain's Studies in Southwest Greenland.—No less decisive in showing the absence of polar whirls are conclusions to be drawn from observations on the borders of the inland-ice of Greenland. At a number of stations on the west and southwest coasts ranging between latitudes 64° and 69°, de Quervain and Stolberg in 1909 conducted ascents of pilot balloons during the spring and early summer, carrying their observations to extreme heights often in excess of 10,000 meters (6⅔ miles),[59] and in one instance of 16,000 meters. In 1912 Drs. Jost and Stolberg supplemented these observations by a second series carried out through the winter season, with results concerning which only a preliminary statement is as yet available.[60]

As has already been explained, the prevailing surface currents at these stations are controlled by the Greenland anticyclones and blow from the southeasterly quadrant, though with considerable modification by local conditions below the level of 1,000 meters. On the basis of his balloon observations, de Quervain has declared that "at least in greater elevations a polar whirl which is in any degree unified and connects the different low pressure regions of the circumpolar latitudes, can, for the time of our observations in Greenland and Iceland, not be thought of." This conclusion was later extended to the remaining portion of the year, as clearly stated in the preliminary announcement of the results of the later series of observations.

[59] A. de Quervain, "Gleichzeitige Pilotaufstiege in Westgrönland und Island, Veranstaltet durch die schweizerisch-deutschen Grönland-expedition und das dänische meteorologische Institut," *Beitr. z. Physik d. fr. Atmosphäre,* Vol. 5, 1913, pp. 132–158.

[60] A. de Quervain, "Quer durchs Grönlandeis, Die schweizerische Grönland-Expedition 1912–13," Munich, 1914, pp. 196, pls. 15, figs. 37 and map.

Distribution of Air Circulation in Successive Levels at the Inland-Ice Margin.—De Quervain's data upon wind direction are so vitally important as to merit some further consideration, particularly as regards the distribution of circulation within the different levels; and I have therefore used them to plot the wind-roses for each of the following ranges of altitude: 0–1,000 meters, 1,000–3,000 m., 3,000–5,000 m. (also separately 3,000–4,000 m. and 4,000–

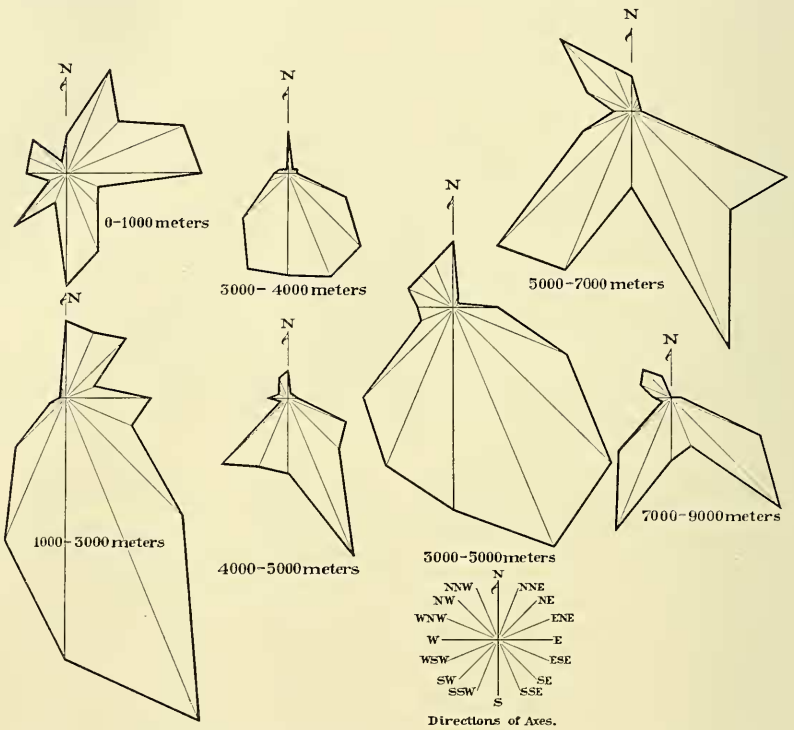

FIG. 7. Wind-roses to illustrate the prevailing winds between the levels indicated at stations on the west and southwest coast of Greenland (from data by de Quervain).

5,000 m,), 5,000–7,000 m., 7,000–9,000 m., and 9,000–11,000 m. For the lower levels between 40 and 58 ascents were available, whereas above 9,000 meters there were 13 and less. The wind-roses have been plotted with weighting for wind force (5 m.p.s. counting as one unit and the nearest unit being taken). Wind

velocities less than 5 m.p.s. were disregarded. The results, which are set forth in Fig. 7, show that below an altitude of 1,000 meters the wind, usually of low velocity, is notably variable and controlled by local conditions. At the level of 1,000 meters the outward flowing currents make their appearance in force and control the circulation up to an altitude of between four and five kilometers, above which level inward blowing currents from the southwesterly quadrant are of equal frequency and of about the same force as the outward blowing currents from the southeast. The clockwise deviation of currents in the anticyclone lead us to suppose that the outward blowing currents start from the interior in a more easterly direction, and that the inward blowing currents from the southwest are almost directly opposed, when they arrive in the interior.

The observations of Wegener made with kites and captive balloons in northeast Greenland, were not generally carried above an altitude of 2,000 meters, though in a few instances considerably higher. They agree among themselves and with those from west Greenland, in showing the presence of relatively variable winds up to about a thousand meters altitude, where these currents are replaced by the strong winds coming down the slope of the inland-ice and increasing in force and in clockwise deviation as one ascends to the limits of the observations. While they are therefore of great interest in revealing the strength and the upward extension of the glacial anticyclone, they have less direct bearing upon the question of circumpolar whirls.[61]

With the above data of Barkow and de Quervain before us, it seems that the time has arrived for laying the specter of the circumpolar whirl, and of returning to an objective basis of reasoning.

Winds About the Margin of the Inland-Ice as a Measure of the Vigor of the Antarctic Anticyclone.

The Zone of Control off "Wilkes Land."—The vigor of a glacial anticyclone may be measured, upon the one hand, by its extension upward from the glacier surface, as has been considered in the last section. Upon the other hand, it may be possible to use the exten-

[61] Wegener, "Drachen- und Fesselballonaufstiege," etc., pp. 55–59.

sion of its circulation outward beyond the glacier margin as an independent measure of its energy. This latter line of inquiry is a particularly fruitful one, for hitherto there has been a general tendency to delimit the zones of wind within the Southern ocean in terms of parallels of latitude.[62] Some years ago under the strong impression that the vigor of the Antarctic anticyclone should dominate within an extra-marginal zone upon the sea, I plotted the wind observations regularly made by the Wilkes Exploring Expedition;[63]

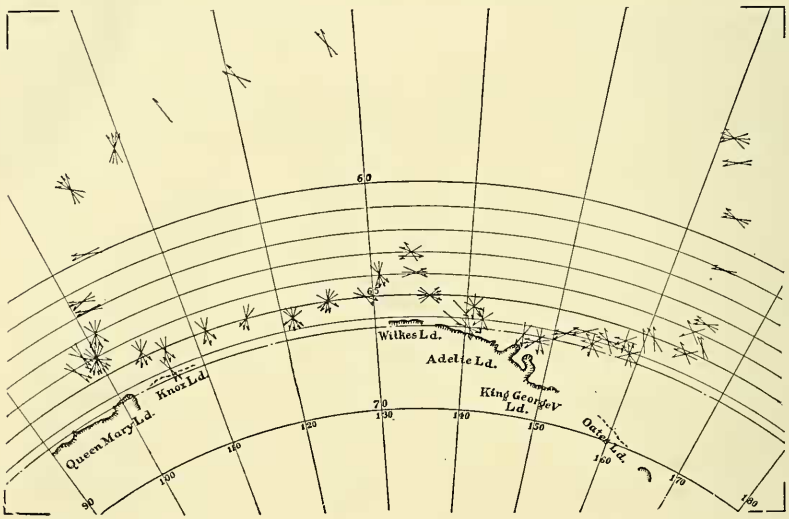

Fig. 8. Map of a portion of Antarctica on which the wind directions recorded by the Wilkes Exploring Expedition have been plotted, but with the margins of the continent corrected so as to accord with Mawson's map. *The arrows point to the wind quarter.*

but was puzzled to find that, whereas there was evident control by the anticyclone within a zone several degrees in width for all points to the westward of long. 150° E., this did not hold for the eastern portion of the route. Now that Mawson has definitely shown[64] Wilkes to have been in error in locating the margin of the continent for that portion of his route to the eastward of longitude 150° E., the apparent lack of harmony which I encountered is suffi-

[62] Cf., for example, Meinardus, l. c.

[63] "Wilkes's Exploring Expedition," Vol. 11 (Meteorology), pp. 272–296.

[64] *Geogr. Jour.*. Vol. 44 (September, 1914), pp. 257–286.

ciently explained. As will be readily seen by reference to Fig. 8, wherever Wilkes was within about three degrees, or some 200 miles, of the inland-ice, the prevailing westerly winds were replaced by southerly and southeasterly ones blowing off the ice. Mawson's own observations leave us in no doubt whatever that this rule of control holds for those margins of the continent which he explored to the eastward of longitude 150° E.

So apparent is the zone of control limited to a belt of 200 miles breadth, at the time of year when Wilkes made his observations, that the winds within and those without this zone for several degrees further, have been plotted in separate roses with results shown in Fig. 9.

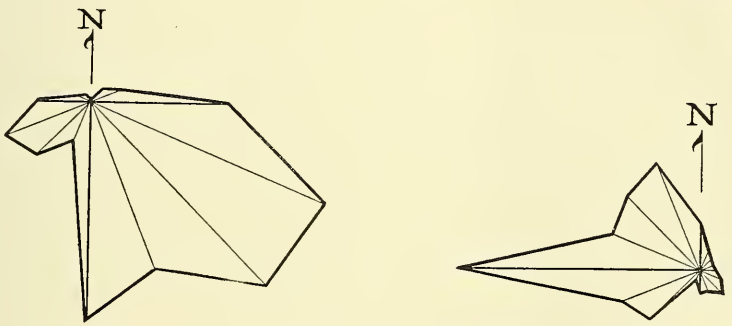

FIG. 9. At the left; wind-rose based upon Wilkes's observations at points distant less than 200 miles from the inland-ice; and, at the right; wind-rose for a zone several degrees in width lying immediately outside the zone of control.

Capt. Davis of the Australian Antarctic Expedition cites an interesting incident in the voyage of the *Aurora* off "Wilkes Land" which indicates he was at the margin of the zone of control.[64a]

The wind observations made by the "Challenger Expedition" at points which we now know to have been near the inland-ice,[65] are confirmation of this conclusion that the effect of the anticyclone extends outward from the margins. Had the observations been those of the first German expedition in 1901–03,[66] offer valuable

[64a] Home of the Blizzard, vol. 2, p. 40.

[65] Challenger Reports, Summary of Results, First part, chart 23.

[66] W. Meinardus, "Deutsche Südpol-Expedition 1901–03," Vol. 4 (Meteor., Vol. 2), pp. 312–319.

taken in the winter season, it is well nigh certain that the zone of control would have been found much wider.

Effect of the Greenland Anticyclone Upon Migrating Cyclonic Depressions.

Supposed Passage of Cyclones Across the Continental Glacier of Greenland.—A question which has been raised in connection with the Greenland continental glacier concerns the interaction of the glacial anticyclone and the migrating cyclones which have been supposed to move in toward the continent. Upon this assumption it might be held, upon the one hand, that the cyclone temporarily overwhelms the anticyclone, and "springing over it" continues upon its course; or, upon the other, that the cyclone is extinguished by the greater vigor of the anticyclone. Evidence which is now fast accumulating shows that, if the cyclones really advance toward the anticyclone, they are at least halted at its margin, and that both become parts of a system of exchanges planetary in its scope. There is, however, upon the assumption stated the possibility that an especially vigorous cyclone in approaching the Greenland coast during one of the weaker stages in the anticyclonic strophe, may make its influence felt not only upon the near side of the anticyclone but beyond it as well.

Nansen's Observations.—Nansen's conclusion after his crossing of Greenland was, that "the plateau seems to be too high and the air too cold to allow depressions or storm centers to pass across, though, nevertheless, our observations show that in several instances the depressions of Baffin's Bay, Davis Strait and Denmark Strait can make themselves felt in the very interior. We experienced, also, one instance of the crossing of a depression in the storm center which passed over us on September 8. This must have been, according to Professor Mohn, a secondary depression which lay over Baffin's Bay some days before."[67] This was, however, in latitude 64° where the inland-ice is extended southward in a relatively narrow tongue. According to de Quervain on but one occasion during the period of his observations on the Greenland west

[67] "First Crossing of Greenland," Vol. 2, p. 496.

coast, was there "an approximation to establishing" a relationship between an extremely rare northwest wind in the upper levels and a deep low area which lay over the Greenland Sea.[68]

The High Pressure Storms and the "Tauben" Depressions Registered at Danmarks-Haven.—In connection with the series of continuous meteorological observations made at Danmarks-Haven in northeast Greenland, Wegener found that while low pressure areas of normal character arrived at the station, they appeared to proceed from the area of the Greenland Sea; and in the absence of parallel observations, he assumed from the southward. The great storms came with an expansion of the high pressure area lying above the continent—so-called "high pressure storms." During the two years over which the observations extended, there passed over the station on two occasions (October and January), what Wegener has called "tauben"[69] depressions. On these occasions the barometer took a deep plunge with reverse movement, as it does during the passage of a tropical cyclone; yet there resulted neither precipitation of any kind nor any wind worthy of mention. This rather remarkable phenomenon Wegener has sought to explain as due to a cyclonic movement which has "sprung over" the anticyclone above the inland-ice, and in so doing has been robbed of its moisture,[70] and also, it would seem, of its circulation.

In view of all the facts, there is reason to doubt that "low" areas ever get across the larger domes of inland-ice; and the storm paths which Vincent has drawn across the continent of Greenland as though it were an expanse of ocean, should be accorded little weight, though it would seem that Wegener has been somewhat influenced by them.[71]

[68] De Quervain, "Gleichzeitige Pilotballonaufstiege, etc.," p. 146.

[69] Perhaps best translated, "barren," or "sterile."

[70] A. Wegener, "Meteorol. Terminbeob. am Danmarks-Haven," pp. 328, 332–334.

[71] E. Vincent, "Sur la marche des minima barométriques dans la région polaire arctique, du mois de septembre 1882 au mois d'août 1883," *Mem. de l'acad. Roy. de Belgique,* 1910.

The Fixed Low Pressure Areas Marginal to the Inland-Ice Masses.

Antarctica.—The Filchner expedition seems to have established the fact that a fixed cyclonic depression lies off the border of the Antarctic continent covering the indentation of the Weddell Sea.[72] In the light of this discovery it now seems highly probably that a similar fixed depression lies above the indentation of the Ross Sea on the other side of the Antarctic regions and in nearly similar relationship to the inland-ice on either side.[73]

Greenland.—It is well known that a fixed low which is especially marked in the winter season lies off the southeast coast of Greenland, usually assumed to wrap itself about Cape Farewell in the form of a crescent, and extends northward into Davis Straits.[74] Recent studies of the free atmosphere by de Quervain at various points on the west and southwest coasts of Greenland indicate that a stationary area of low barometer (probably continuous with this) extends northward in Baffin's Bay as far at least as Disco Island.[75] The simultaneous studies carried out with pilot balloons at Akureyri in Iceland, indicate clearly that a stationary depression lies over the Greenland Sea to the northward of Iceland and between the Greenland and Norwegian coasts.[76] The Danes from the journeys of bottles set adrift during the expedition of 1906–08, determined that the currents within this sea are such as would indicate a stationary cyclone, since movements were southward along but off the Greenland coast until near the latitude of Iceland, where they are deflected eastward and later northward so as to follow the trend of the Norwegian coast.[77] Thus about both the glacial anticyclone

[72] L. c.

[73] See R. F. Scott, "Voyage of the *Discovery*," Vol. 2, p. 412; L. Bernacchi, "To the South Polar Regions, 1901," p. 298; W. S. Bruce, "Polar Explorations," New York, 1911, p. 187; Simpson, "Scott's Last Expedition," Vol. 2, p. 324.

[74] Cf., for example, Berghaus, "Atlas der Meteorologie," Pls. 33–34.

[75] A. de Quervain, "Gleichzeitige Pilotballonaufstiege in Westgrönland und Island," *Beiträge z. Physik. de Freien Atmosphäre,* Vol. 5, 1913, p. 145.

[76] de Quervain, l. c., p. 146.

[77] Alf. Trolle, "Danmark-Ekspeditionen til Gronlands Nordostkyst, 1906–08, under ledelse af L. Mylius-Erichsen," *Med. om Gronl.,* Vol. 41, 1913. See also, Sir John Murray and Dr. J. Hjort, "The Depths of the Ocean," London, 1912, p. 284.

groups it would now appear that the stationary "lows" are located where land barriers oppose a progressive movement.

The Rôle of the Glacial Anticyclones of High Latitudes in the General Air Circulation.

Circulation is Through Cyclones and Anticyclones, Not Merely Within Them.—In an earlier section it has been shown how the preconceived notion of a polar cyclone, the circumpolar whirl, has held back the advance of knowledge where the polar regions are concerned; and how this theory has now been effectually disposed of by the observations of de Quervain, Stolberg, Barkow and others.

The progressing cyclones within the atmosphere were by Ferrel assumed to be symmetrical in their distribution, with warm upward-moving central portions and cold marginal rims; to circulate the same body of air which repeatedly passes through certain paths; and to have their origin in areas of excessive local insolation. Instead of being symmetrical, as has now so generally been assumed, the study of isotherms in connection with cyclones has shown that these lines usually trend in the United States from southwest to northeast, crossing the cyclone by quite regular paths instead of being circular about its center. The evidence derived from international cloud observations would seem to show that the cyclone is a form of circulation *through which fresh portions of the atmosphere continue to stream;* and both cyclones and anticyclones are to be regarded as eddies which at the surface of the earth have each a hot and a cold side. The same air streams through both, its progress when projected upon the earth's surface being a sinuous line.

Belts of Progressing Cyclones and Anticyclones about the Antarctic Glacial Anticyclones.—The southern hemisphere, being less invaded by the continents, offers for the purposes of study some advantages on the side of relative simplicity, and it has in its meteorological aspects been recently comprehensively treated by Lockyer,[78] who has taken full account of the results of Antarctic

[78] W. J. S. Lockyer, "Southern Hemisphere Surface Air Circulation," etc., Solar Physics Committee under direction of Sir Norman Lockyer, London, 1910, pp. 109, pls. 15.

explorations and has endeavored to show the conjugate relationship of the Antarctic anticyclone area with successive zones of cyclones and anticyclones which migrate in an easterly direction around it. Thus it is found that between the low pressure zones lying within the tropics, and the fixed high pressure area above Antarctica, there are centered near the latitude of 40° S., a series of broad anticyclones which progress eastwardly and produce the effect of a zone of mean high pressure.[79] To the southward of this series of anticyclones and centered near the latitude of 60° S., there are a series of more vigorous cyclones of smaller diameter but progressing eastwardly at about the same angular rate. As we now know from later observations, the stationary cyclones lying over the Weddell and Ross Seas, establish further connection with the anticyclones above the Antarctic continent.

The cold outward flowing currents from the Antarctic continent upon reaching the zones of progressing cyclones are believed by Lockyer to ascend in them upon the west side, thus accounting for the cold western half of these cyclones near the ocean level.

The Australian Antarctic Expedition appears now to have supplied the evidence for such a rise of the air at the southern margin of the progressing cyclones near the borders of Adelie Land. As Mawson puts it:

> "It appeared as if we were situated on the battlefield, so to speak, of opposing forces. The pacific influence of the 'north' would hold sway for a few hours, a whole day, or even for a few days. Then the vast energies of the 'south' would rise to the bursting point and a 'through blizzard' would be the result."

At this junction zone of the glacial anticyclone with progressing cyclones, the air rises to produce rotating cumulus clouds, and it seems not unlikely that the interesting "whirlies" are connected with this uprise.[80]

The air having ascended in a cyclone on its journey northward toward the equator is believed next to pass downward through the progressing anticyclones to the northward, and to reach the ocean's surface as the warm current on the west side of these eddies.

[79] W. J. Humphreys, "On the Physics of the Atmosphere," *Jour. Franklin Inst.*, 1913, pp. 222–223.

[80] Mawson, "The Home of the Blizzard," Vol. 2, pp. 157–8 (fig.).

Mawson's demonstration through wireless communications that the hurricanes of Adelie Land preceded by some 48 hours the arrival of storms at the Australian south coast, would seem to support strongly this view (Fig. 10).[81]

Fig. 10. Map to illustrate the prevailing atmospheric conditions to the southward of Australia (compiled from maps by Lockyer and Mawson).

The Rôle of the Glacial Anticyclones in the General Air Circulation to Draw Down the Air of the Upper Stratum in the Troposphere and to Direct it Equatorward.—From these geographical relationships it appears highly probable that the glacial anticyclones above the inland-ice masses stand in a definite conjugate relationship to stationary cyclones above embayments of the continent.

[81] Cf., also, "The Home of the Blizzard," Vol. 2, fig. opp. p. 141.

The glacial anticyclones of Greenland and Antarctica through drawing down of air from the upper levels and as a consequence of a throughout centrifugal surface circulation, are a very important factor in reversing the high poleward currents within high latitudes and directing them equatorward. The source of energy which

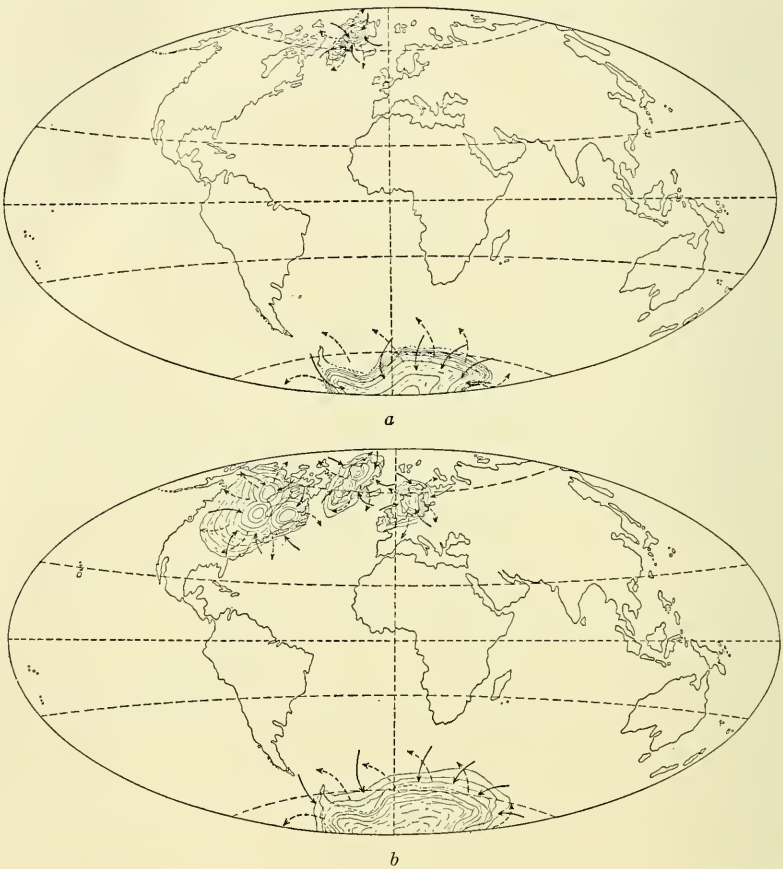

FIG. 11. (*a*) World map to show the present position of the earth's wind poles where the air of the upper stratum within the troposphere is in large part returned to the surface in glacial anticyclones. (*b*) World map to show the corresponding wind poles of the Pleistocene period.

maintains the whole system in motion, is of course the sun's heat concentrated within the tropics and in large measure absorbed over the continental glaciers (Fig. 11a). It is to be assumed that the

uplands of northeastern Siberia, the smaller masses of inland-ice within the Arctic region, and in fact any area where heat radiation is large, contribute in lesser measure to draw down the upper air currents and reverse their direction. It is the unhindered radiation of desert areas which is responsible for the anticyclonic conditions over them in the winter season. Abnormally high insolation in the summer season may, however, overbalance this effect and produce cyclonic effects. The moisture locked up in the ice needles of the cirri and related cloud forms above those areas of ocean where evaporation is large, is thus returned to the earth and especially within the glacial anticyclones. Of this moisture a portion is added to the glacier mass, but at the present time a much larger portion is blown off the glacier surface into the sea and so returned to its source in the waters of the ocean.

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Ann Arbor,
March 12, 1915.